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Study of Electrical and Chemical Propulsion Systems for Auxiliary Propulsion of Large Space Systems

Volume 1 Executive Summary

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16. Abstract

This document is an executive summary of the final report prepared under Contract NAS3-21952 "Study of Electrical and Chemical Propulsion Systems for Auxiliary Propulsion of Large Space Systems" and covers five analytical tasks. Task 1 includes a literature search followed by selection and definition of seven generic spacecraft classes. Task 2 covers the determination and description of important disturbance effects. Task 3 applies the disturbances to the generic spacecraft and adds maneuver and stationkeeping functions to define total auxiliary propulsion systems requirements for control. The important auxiliary propulsion system characteristics are identified and sensitivities to control functions and large space system characteristics determined. In Task 4, these sensitivities are quantified and the optimum auxiliary propulsion system characteristics determined. Task 5 compares the desired characteristics with those available for both electrical and chemical auxiliary propulsion systems to identify the directions technology advances should take.

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FOREWORD

This document has been prepared by the Boeing Aerospace Company for the National Aeronautics and Space Administration, Lewis Research Center in compliance with Contract NAS3-21952, "Study of Electrical and Chemical Propulsion Systems for Auxiliary Propulsion of Large Space Systems."

Study results are documented in two volumes. Volume 1, this document, is a short executive summary which highlights the significant data, results and conclusions. Volume 2 is a detailed report covering all study activities.

Mr. John D. Regetz, Jr., and Mr. Joseph E. Maloy were the NASA Contracting Officer's technical representatives. Boeing performance on the contract was under the management of Dr. James P. Clark. Mr. William W. Smith was the technical leader, with participation from Richard M. Gates, Barry Binns and George Roe.

ABSTRACT

This document is an executive summary of the final report prepared under Contract NAS3-21952 "Study of Electrical and Chemical Propulsion Systems for Auxiliary Propulsion of Large Space Systems" and covers five analytical tasks. Task 1 includes a literature search followed by selection and definition of seven generic spacecraft classes. Task 2 covers the determination and description of important disturbance effects. Task 3 applies the disturbances to the generic spacecraft and adds maneuver and stationkeeping functions to define total auxiliary propulsion systems requirements for control. The important auxiliary propulsion system characteristics are identified and sensitivities to control functions and large space system characteristics determined. In Task 4, these sensitivities are quantified and the optimum auxiliary propulsion system characteristics determined. Task 5 compares the desired characteristics with those available for both electrical and chemical auxiliary propulsion systems to identify the directions technology advances should take.

KEY WORDS

Attitude control
Auxiliary propulsion
Large space systems
Shape control
Stationkeeping

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1.0 INTRODUCTION AND SUMMARY

Planned spacecraft and the projections of probable vehicles in the future by government and industry show an unmistakable trend towards larger structures. Many of these vehicles will require construction in low earth orbit, followed by transfer to geosynchronous orbit. Once on station, the general requirement is for a very long operational life. This study is part of an ongoing process to determine the propulsion requirements needed to support such space activities. Although there may be some overlapping functions, propulsion divides into the two groupings of prime and auxiliary propulsion. Prime propulsion is used to perform orbit transfer while auxiliary propulsion takes on the attitude control, shape control and stationkeeping tasks.

This study considered auxiliary propulsion only and supplements other work in progress that is examining prime propulsion needs. The objective was to determine the direction auxiliary propulsion research and development should take to best meet upcoming needs. The approach used was to define the important electrical and chemical auxiliary propulsion characteristics in terms of the demands that will be imposed by future spacecraft. Comparison of these desired characteristics and capabilities with those presently available was then used to identify deficiencies.

The study was divided into five tasks:

1. Characterization of Large Space Structures (LSS)
2. Establishment of Disturbance Characteristics
3. Establishment of Auxiliary Propulsion System (APS) Characteristics and Requirements
4. Interaction Between Auxiliary Propulsion System Characteristics and Large Space System Characteristics
5. Determination of Electrical and Chemical Propulsion Technology Advances Required

Understanding the basic assumptions used in the study is crucial to understanding and applying the conclusions. The key assumptions are:

1. LEO deployment, LEO-GEO low thrust transfer, GEO operation
2. 10 year LSS lifetime
3. CP-CG = 5 percent of maximum dimension
4. RF mesh and truss work assumed to have 95 percent transmission factor
5. 30 cm ion thruster technology used as SOA electric system capability

The first assumption indicates that only structures associated with GEO missions were studied. Disturbances for various LSS angles were analyzed at LEO, during orbit transfer, and at GEO. A ten year lifetime assumption

sized the stationkeeping fuel mass and was used as a benchmark to compare SOA component lifetimes. The CP-CG offset assumption was necessary because of the idealized nature of the configurations used for each generic class. This assumption was critical in determining torques due to solar pressure and aerodynamic torques. The sensitivity to this assumption is greatest at LEO where aerodynamic torques dominate. The fourth assumption was based on work done by Boeing and the Harris Corporation. This assumption may not hold true for each design and each LSS orientation; however, the exact transmissivity number is very difficult to estimate given the general nature of the study. The final assumption indicates that we did not consider any other electric propulsion technology such as MPD, pulsed plasma, rail gun, etc. in the study. A summary of the major conclusions are shown below:

- Electrical APS are required at GEO from fuel mass considerations and current SOA systems have adequate thrust levels and I_{sp} for long term (>5 year) GEO operation of deployable (<200m) LSS. For multiple Shuttle launched, medium and large sized (>200m) LSS, clustering of up to 20 SOA electric thrusters required.

- Chemical systems are necessary to meet the thrust level requirements at LEO (300 km) and during LEO-GEO transfer environments.

- LEO (300 km) construction of very large LSS (>1000m) is unlikely due to large environmental disturbances.

- LSS operational philosophy (LEO vs. GEO deployment, APS resupply, etc.) is a key driver to APS technology needs.

- For LSS with large surface areas, the difference between deploying at 300 km and deploying at 500 km can increase APS hardware mass by an order of magnitude.

- Start-up delays of 30 minutes or more for electric systems cause large (>1/2 degree) pointing accuracy losses and significant structural damping losses.

- Electric thruster lifetime must be extended to 35000 hours due to the long (40 percent) stationkeeping duty cycles needed to reduce thrust levels to SOA capability.

- Much attitude control effort can be obtained without cost by combining attitude control and stationkeeping functions. Hence, control moment gyros and inertia wheels may not be used on many LSS.

- Because of the wide variation in thrust requirements from LEO, LEO-GEO transfer, and GEO, hybrid systems (chemical plus electrical) may be indicated.

2.0 CHARACTERIZATION OF LARGE SPACE STRUCTURES

There are a large number of diverse structures either planned or proposed for future space missions. The initial task in this study was to reduce these concepts to a manageable set by defining a relatively small number of unique generic classes of structures which would be associated with as many of the concepts identified as possible. During the course of the study, both erectable and deployable structures were considered. The initial phase of the study concentrated on large primarily erectable structures which would need one or more shuttle launches to transport to low earth orbit (LEO). It was found that the great majority of these vehicles fell naturally into three classes - planar array, single antenna systems, and multiple antenna systems. Several subdivisions appeared appropriate to represent particular control system characteristics. In all, seven generic classes were defined for the multiple shuttle launched LSS. These classes are shown in Figure 1.

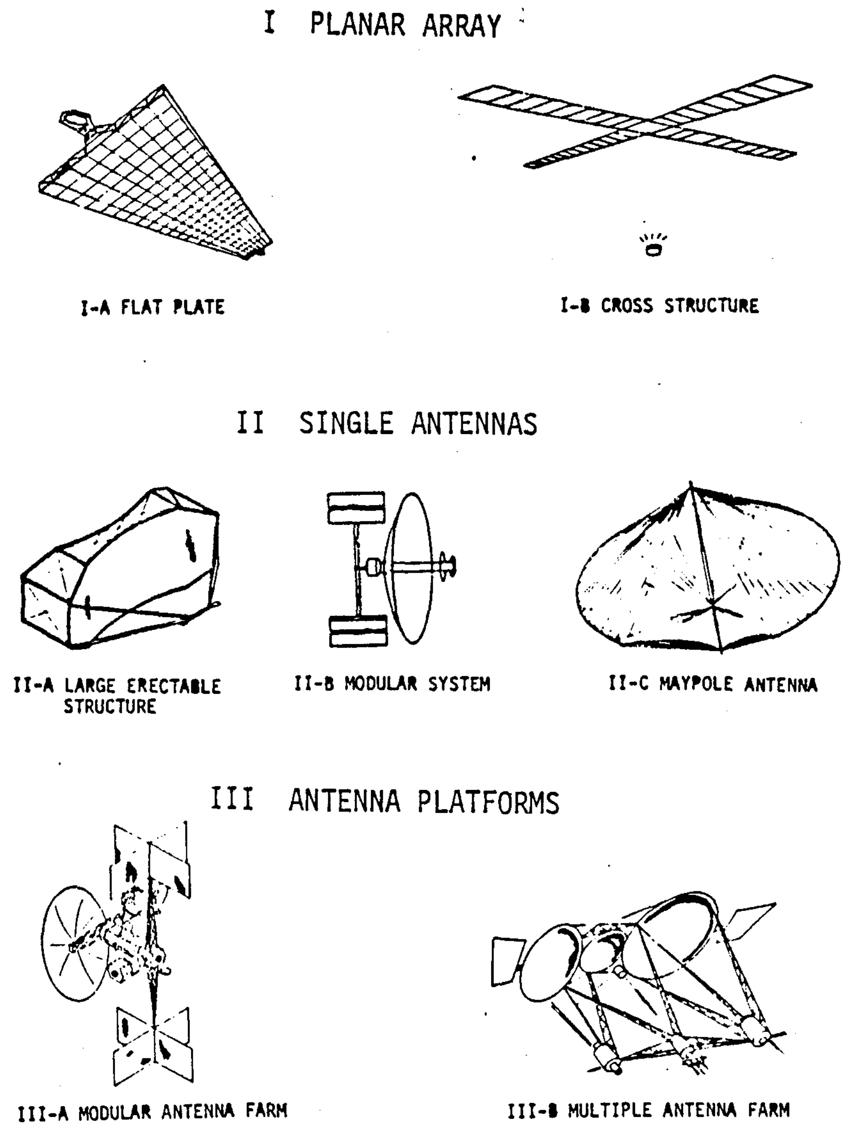

FIGURE 1 GENERIC CLASS SUBDIVISIONS

To gain insight into shorter term (1990-2000) auxiliary propulsion requirements, the generic classes were reviewed assuming the vehicles were limited to a single shuttle payload. The three main classes remained unchanged, however only deployable antennas and truss work were allowed. This limitation changed the nature of the plate structure to reflect the results of previously performed packaging studies. The tetrahedral truss was found to be the leading candidate for large deployable planar trusses. Figure 2 illustrates the deployable plate concept. As an additional subdivision for the single shuttle launched vehicles, the plate structure was considered as a simple truss without any covering and also with a solar array blanket stretched over one surface.

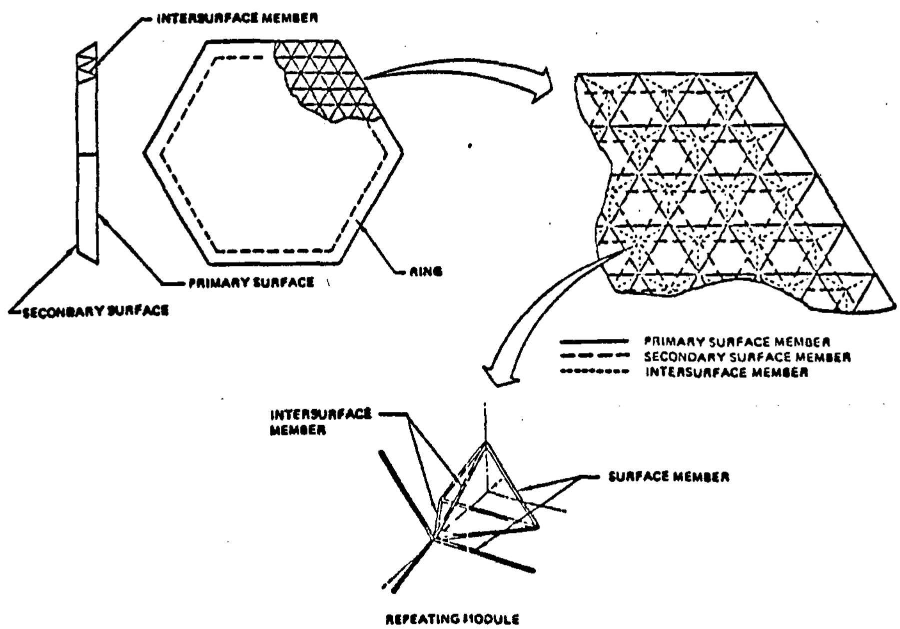

FIGURE 2 PLATE STRUCTURE UTILIZING TETRAHEDRAL TRUSS

Table 1 shows the relevant properties for each LSS class considered in this study. As shown in Table 1, a small, medium, and large size were selected for each class to analyze in detail.

A scaling parameter from which all mass properties were defined was identified for each class. The effective area/mass ratio differs from the total area to mass ratio for the RF mesh antennas and truss structures without a solid surface covering. The effective area for solar pressure and aerodynamic calculations is taken to be five percent of the actual area for RF and truss structures.

3.0 DISTURBANCE TORQUE EVALUATION

To establish auxiliary propulsion requirements, a detailed examination of the LSS environment was conducted. Important sources were determined to be:

TABLE 1 GENERIC CLASS CHARACTERISTICS

GENERIC CLASS	SCALING PARAMETER	SIZE	MASS (KG)	AREA/MASS (M^2/KG)	EFFECTIVE A/M (M^2/KG)
MULTIPLE SHUTTLE LAUNCH					
I A PLATE	LENGTH (M)	SMALL (30 M)	170	1.33	1.33
		MEDIUM (700 M)	91875	1.33	1.33
		LARGE (21000 M)	8.27×10^7	1.33	1.33
I B CROSS	LENGTH (M)	SMALL (40 M)	560	.071	.004
		MEDIUM (500 M)	7000	.071	.004
		LARGE (4000 M)	56000	.071	.004
II A BOX	LENGTH (M)	SMALL (82 M)	12300	.027	.002
		MEDIUM (600 M)	90000	.027	.002
		LARGE (1300 M)	1.95×10^5	.027	.002
II B MODULAR ANTENNA	ANTENNA DIAMETER (M)	SMALL (15 M)	2025	.186	.104
		MEDIUM (60 M)	8100	.449	.117
		LARGE (200 M)	27000	1.085	.135
II C MAYPOLE ANTENNA	ANTENNA DIAMETER (M)	SMALL (30 M)	101	7.030	.350
		MEDIUM (250 M)	487	101.08	5.050
		LARGE (1500 M)	2625	661.08	33.000
III A ORBITAL ANTENNA FARM	ANTENNA DIAMETER (M)	SMALL (15 M)	3000	.147	.036
		MEDIUM (35 M)	7000	.305	.044
		LARGE (60 M)	12000	.501	.053
III B SERIES OF ANTENNAS	NUMBER OF ANTENNAS	SMALL (2)	40270	.145	.012
		MEDIUM (6)	1.21×10^5	.145	.012
		LARGE (10)	2.01×10^5	.145	.012
SINGLE SHUTTLE LAUNCH					
I PLATE STRUCTURE W/O BLANKET	LENGTH (M)	SMALL (30 M)	506	.865	.043
		MEDIUM (100 M)	1618	4.014	.201
		LARGE (250 M)	3672	11.055	.553
II PLATE STRUCTURE W/BLANKET	LENGTH (M)	SMALL (30 M)	1334	.438	.438
		MEDIUM (100 M)	11350	.572	.572
		LARGE (150 M)	24420	.598	.598
III MODULAR ANTENNA	ANTENNA DIAMETER (M)	SMALL (15 M)	2300	.165	.091
		MEDIUM (60 M)	8375	.433	.113
		LARGE (200 M)	18017	1.980	.236
IV SERIES OF ANTENNAS	NUMBER OF ANTENNAS	SMALL (2)	7500	.826	.085
		MEDIUM (3)	11250	.802	.085
		LARGE (4)	15000	.764	.084

radiation, gravity gradient, aerodynamic, and orbit perturbation. Magnetic torques were found to be too dependent on specific vehicle payloads to be easily characterized and estimates indicated that the magnitudes of these torques were negligible. Thermal effects were also eliminated from consideration. Thermal effects have many important consequences but were not found to be significant as regards auxiliary propulsion, particularly when specific vehicle payloads were not considered.

In the analysis of radiation disturbances for earth orbital missions, two sources of radiation require consideration. The primary disturbance is from direct solar radiation which contributes both radiation forces from photons and a plasma force from the solar wind. A secondary disturbance is earth illumination which can be reflected sunlight or infrared emission. Earth illumination is a negligible consideration above 10000 km, but was examined in lower orbits. The magnitude of radiation disturbances in LEO even under worst case LSS orientation and significant CP-CM moment arms was negligible in comparison to gravity gradient and aerodynamic torques. At geostationary orbit, radiation pressure contributes to both torque and stationkeeping force requirements and is a larger disturbance than gravity gradient for some structures.

Aerodynamic effects on spacecraft are significant for orbital altitudes up to approximately 1000 km. The forces due to radiation pressure and aerodynamic drag and lift are of similar magnitude for altitudes between 600 and 1000 km. Beyond 1000 km, the radiation-related forces are typically much greater than those arising aerodynamically. Free-molecular flow was assumed for the aerodynamic analysis. This assumption implies that each particle interacts with the structure on an individual basis and that no inter-molecular effects occur. Average atmospheric density was used and no variations due to solar flux or night/day density changes were included in the analysis.

Gravity gradient torques for LSS can impose significant requirements on the auxiliary propulsion system. These torques are of the same order of magnitude as aerodynamic torques in LEO and are dominant torques for LSS with large differences in inertias between axis. Orientation angle determines the magnitude of gravity gradient torques and was varied for different flight conditions.

Stationkeeping requirements stem from three sources. The smallest source of orbit perturbation is longitudinal drift caused by the triaxiality of the earth. The other two sources, lunar/solar gravity perturbations and solar pressure forces, are much larger for LSS.

It was found that correction frequency and duty cycle greatly affected the thrust levels required for stationkeeping. Duty cycles of 40-50 percent and a correction frequency of once/orbit seemed to be optimal for electric propulsion application. This combination of duty cycle and correction frequency allowed thrust levels to be low enough for available electric thrusters and add relatively small delta-V additions due to cosine losses in thrust efficiency.

To illustrate the disturbance torque requirements for LSS, the single shuttle launched vehicles serve as a good example. The torque levels for

three orbit altitudes and two LSS orientations were determined as well as a LEO-GEO transfer maneuvering requirement. The orbit transfer requirement was based on a time optimal continuous thrust LEO-GEO transfer in which all thrust vector control (TVC) is supplied by the APS on the payload. Very low thrust transfers may require some assistance in meeting the in and out of plane TVC requirements due to the very large inertias of deployed LSS.

The definition of LSS angle is shown in Figure 3 for the three main classes. LSS angle determines which of the disturbance forces dominate at a given altitude. Figure 4 illustrates the composite torque breakdown of the plate structure with blanket at two LEO altitudes. For each structure in the study a CP-CG offset of five percent of the maximum dimension was assumed. At 300 km, aerodynamic torques totally dominate the disturbances and the LSS angle giving the largest effective area is 90 degrees. At 500 km, aerodynamic disturbances remain the largest force; however, gravity gradient torques now contribute substantially to the total torque and a worst case angle of 60 degrees results.

Table 2 summarizes the disturbance torque requirements for single shuttle launched LSS. Several observations can be made from this summary. First, for LSS with large surface areas, requirements at 300 km are a factor of 5-10 greater than those of a 500 km,. Second, requirements for an LSS angle of 10 degrees in LEO are a factor of five or more less than those at the worst case LSS angle. Finally, in GEO, solar pressure poses as large a disturbance force as gravity gradient, hence solar stationkeeping thrust requirements are on the order of thrust requirements imposed by disturbance torques.

TABLE 2
SINGLE SHUTTLE LAUNCHED DISTURBANCE TORQUE REQUIREMENTS SUMMARY

CLASS	SIZE	LEO-GEO TRANSFER MANEUVERING (START ALTITUDE 300 KM)	TORQUE REQUIREMENTS (N-M)								
			ALTITUDE								
			300 KM			500 KM			GEOSYNCHRONOUS ORBIT		
			LSS ANGLE		WORST CASE ANGLE (DEG)	LSS ANGLE		WORST CASE ANGLE (DEG)	LSS ANGLE		WORST CASE ANGLE (DEG)
			10°	WORST CASE		10°	WORST CASE		10°	WORST CASE	
PLATE W/O BLANKET	30 M	.069	.055	.350	75	.014	.060	50	.0003	.0004	45
	100 M	2.46	1.80	11.2	75	.500	2.20	52	.013	.019	45
	250 M	34.88	22.00	205.0	75	6.30	31.0	53	.250	.280	45
PLATE W/BLANKET	30 M	.153	.810	6.80	90	.120	.500	72	.006	.007	45
	100 M	16.31	32.0	230.0	83	5.30	23.0	58	.230	.280	45
	150 M	96.40	112.0	850.0	80	28.0	108.0	55	.850	1.05	45
MODULAR ANTENNA	15 M	.054	.170	1.20	90	.014	.088	86	.0015	.002	45
	60 M	1.37	3.30	21.0	83	.550	2.20	58	.022	.026	45
	200 M	15.07	46.0	305.0	90	4.80	22.0	73	.300	.320	45
SERIES OF ANTENNAS	2	4.37	1.50	11.5	45	1.50	9.90	45	.200	.800	45
	3	6.65	9.50	61.0	45	9.50	53.0	45	.065	.260	45
	4	8.88	30.0	195.0	45	30.0	160.0	45	.013	.042	45

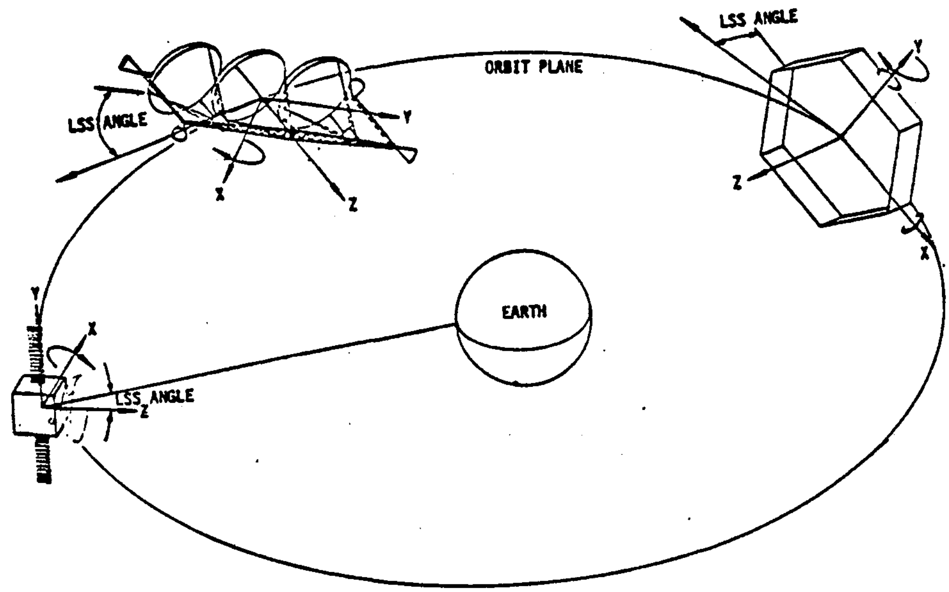

FIGURE 3 LSS ANGLE DEFINITION

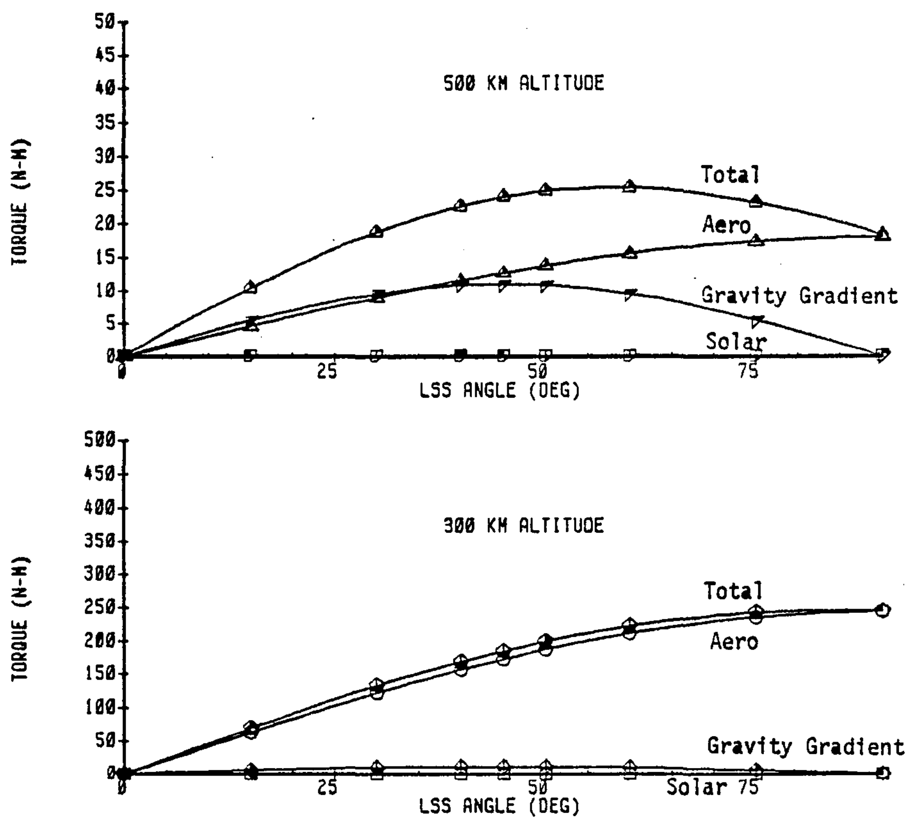

FIGURE 4 TORQUE COMPOSITE BREAKDOWN
SINGLE SHUTTLE LAUNCHED DEPLOYABLE STRUCTURE
PLATE STRUCTURE WITH BLANKET - MEDIUM (100M)
CP - CG = 5% OF MAXIMUM DIMENSION

4.0 THRUST LEVEL DETERMINATION

To determine the thrust level requirements for both large erectable structures and the single shuttle launched LSS, the disturbance force and torque analysis results were utilized along with a set of thrust location assumptions on the LSS.

Each structure was assigned thruster locations with the exception of the multiple shuttle launched plate structure which was assumed to have distributed thrusters. The method of distribution is shown in Figures 5 and 6. This thruster configuration was chosen based on the APS/LSS interactions study results discussed in Section 5. Thruster distribution on the remaining classes was based on a set of five assumptions. These are listed in Table 3 below. An illustration of thruster locations for deployable LSS is shown in Figure 7.

1. Thrusters were located to assure dual redundancy
2. Chemical systems have a fixed orientation (no gimbal freedom)
3. Electric thrusters have a ± 45 degree gimbal capability
4. Thruster distribution was capable of zero ΔV addition maneuvering
5. Maximum moment arms utilized where possible around large inertia axis

Table 3: Thrust Location Determination Assumptions

Under the assumptions listed in Table 3, electric thruster thrust requirements were slightly larger than those of chemical thrusters. The difference in requirements was minimized by judicious choice of thruster locations and the results of the thrust level determination study for chemical or electrical systems differed little in thrust magnitude requirements. Factors such as plume impingment and power distribution requirements were not taken into consideration in this study. Using the assumed thrust locations, Table 4 shows the thrust level requirements for the multiple shuttle launched vehicles and Table 5 gives the results for the single shuttle launched LSS.

In Table 4, there are four categories of thruster sizing. The LEO maximum requirement corresponds to a worst case LSS orientation at 300 km altitude. The LEO-GEO transfer requirement is based on the TVC requirements imposed by a time optimal continuous thrust trajectory. The GEO maximum requirement results from a worst case LSS orientation at GEO, whereas the GEO nominal requirement stems primarily from normal operation stationkeeping requirements. The thrust level requirements for LEO are more than one order of magnitude greater than those at GEO. Furthermore, for the largest plate structure examined (21000m x 5250m) the thrust requirements in LEO are so large as to preclude designing the APS to recover from a worst case orientation. It is also noted that currently available electric systems (limited to 0.13 N thrust) do not have sufficient thrust levels to meet the thrust requirements of most of the categories listed.

Table 5 takes a detailed look at the thrust requirements for single shuttle launched deployable LSS. In this study, the thrust level requirements

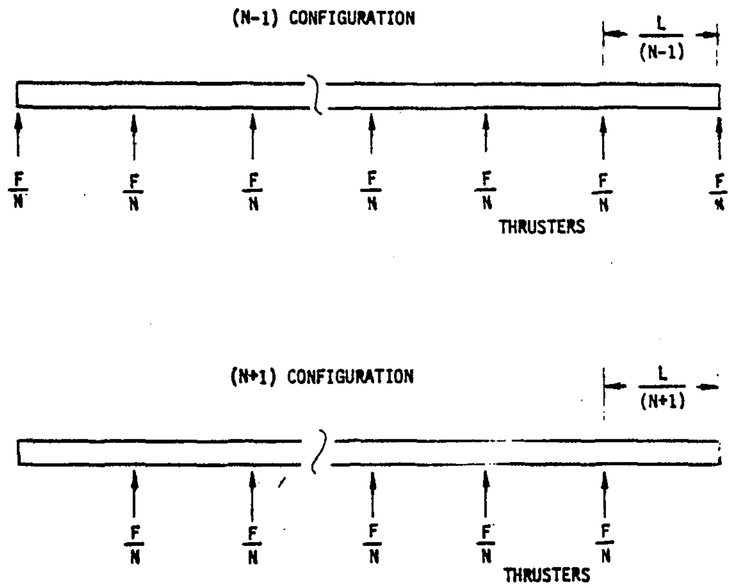

FIGURE 5 (N-1) AND (N+1) THRUSTER CONFIGURATION

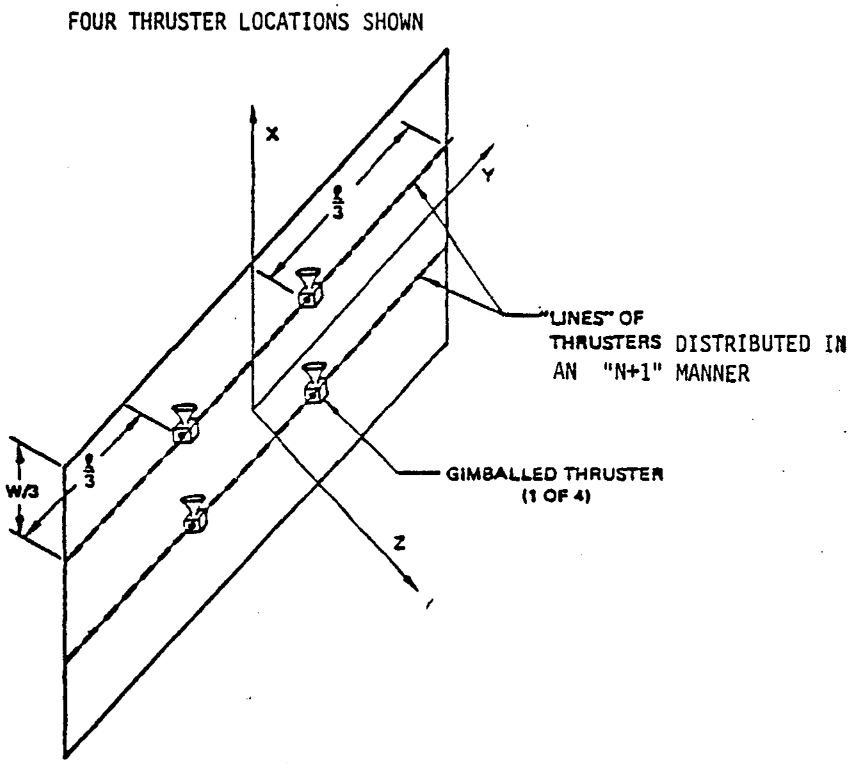

FIGURE 6 MULTIPLE SHUTTLE LAUNCHED PLATE STRUCTURE THRUSTER LOCATIONS

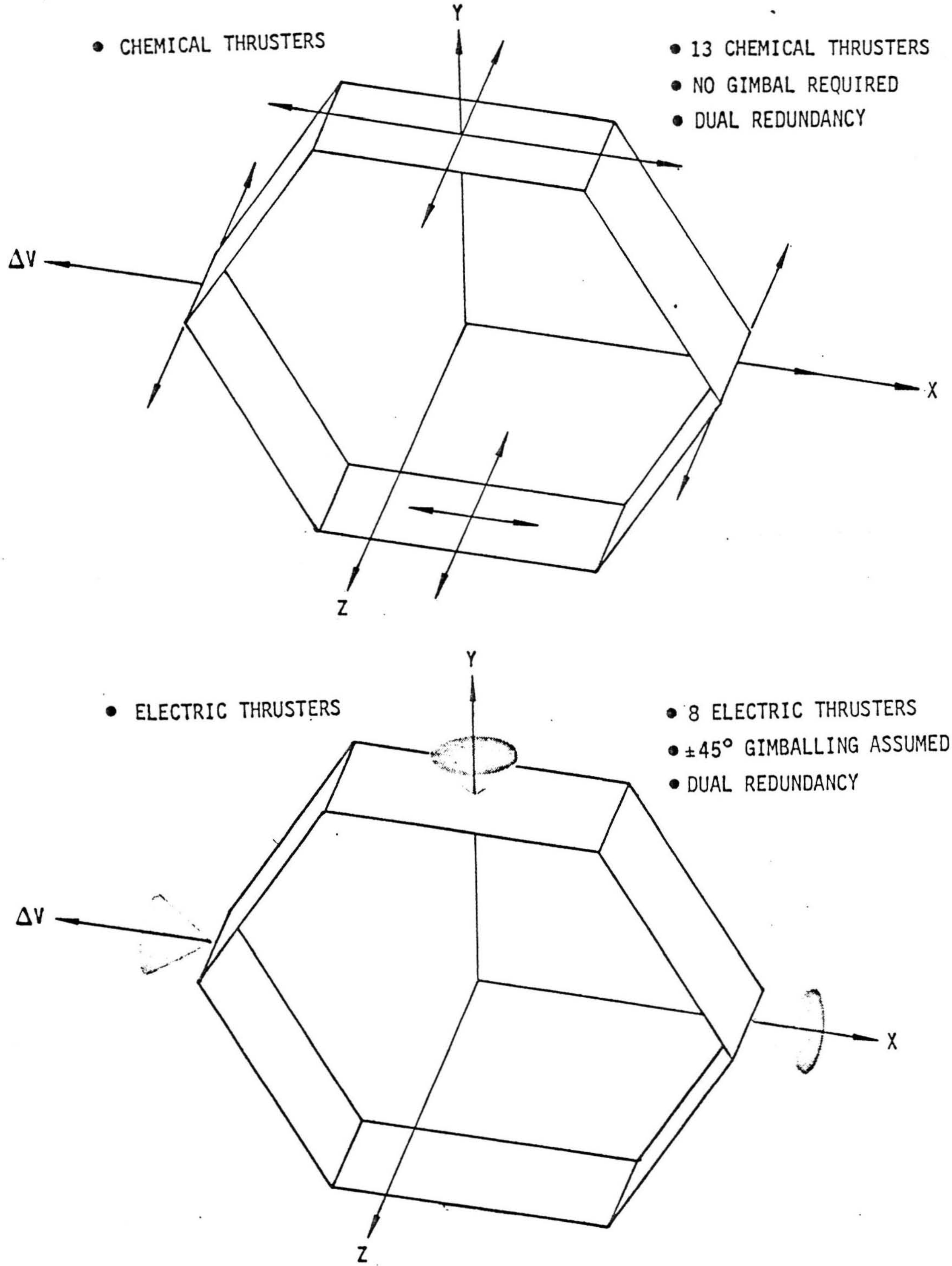

FIGURE 7 DEPLOYABLE TETRAHEDRAL TRUSS THRUSTER LOCATIONS

TABLE 4 THRUST REQUIREMENTS SUMMARY FOR MULTIPLE SHUTTLE LAUNCHED STRUCTURES

STRUCTURE	SIZE	# THRUSTERS	THRUST/THRUSTER REQUIRED: LEO MAXIMUM	LEO-GEO TRANSFER	GEO MAXIMUM	GEO NOMINAL
PLATE	SMALL (30 m)	4	.04	.0022	.0018	.0018
	MEDIUM (700 m)	4	21	20	.92	.92
		24	2.2	3.5	.16	.16
		100	.7	.9	.04	.04
	LARGE (21000 m)	4	610000	46000	6200	3310
		24	62000	8000	1080	570
		100	15100	1950	260	137
MODULAR ANTENNA	SMALL (15 m)	8	.14	.07	.009	.009
	MEDIUM (60 m)	8	1.2	.75	.034	.032
	LARGE (200 m)	8	62	60	.23	.105
		32	16	14	.06	.03
		80	6.4	5.6	.024	.012
SERIES OF ANTENNAS	SMALL (2)	4	.113	8.75	.04	.04
	MEDIUM (6)	4	6.75	32.5	.79	.48
		24	1.13	5.42	.13	.08
		96	.28	1.35	.03	.02
	LARGE (10)	4	26.3	54.0	2.80	.78
		24	4.4	9.0	.47	.13
		96	1.1	2.3	.12	.03

TABLE 5 THRUST /THRUSTER SUMMARY FOR SINGLE SHUTTLE LAUNCHED DEPLOYABLE STRUCTURES

CLASS	SIZE	DISTURBANCE TORQUE 300 km 10°	300 km WORST CASE	500 km 10°	500 km WORST CASE	LEO - GEO TRANSFER	GEO DISTURBANCE WORST CASE	GEO STATIONKEEPING @ 0.4 DUTY CYCLE ONCE/ORBIT	ONCE/WEEK
PLATE W/O BLANKET	30 m	0.004	0.025	0.001	0.004	0.005	0.0001	0.002	0.015
	100 m	0.038	0.240	0.011	0.049	0.057	0.0004	0.007	0.050
	250 m	0.187	1.739	0.054	0.261	0.297	0.0020	0.022	0.170
PLATE W/BLANKET	30 m	0.056	0.480	0.008	0.035	0.011	0.0055	0.008	0.050
	100 m	0.700	4.880	0.112	0.488	0.346	0.0059	0.075	0.530
	150 m	1.584	12.020	0.396	1.527	0.346	0.0150	0.160	1.100
MODULAR ANTENNA	15 m	0.120	0.504	0.010	0.060	0.037	0.0115	0.004	0.035
	60 m	1.500	9.540	0.250	1.000	0.625	0.0115	0.016	0.125
	200 m	16.800	55.790	1.755	8.050	5.515	0.1170	0.041	0.300
SERIES OF ANTENNAS	2	0.035	0.272	0.035	0.233	0.103	0.0020	0.010	0.105
	3	0.150	0.962	0.150	0.836	0.105	0.0040	0.020	0.155
	4	0.353	2.298	0.353	1.880	0.105	0.0100	0.030	0.210

categories were refined to include LSS orientation and three orbit altitudes. Here the impact of LEO altitude and LSS angle can be seen. At 500 km and 10 degrees LSS angle only the very largest LSS have requirements that could not be met by SOA 30 cm ion propulsion. At 300 km and a worst case orientation only the 30 m plate w/o blanket could use electric APS. At GEO, electric propulsion thrust levels seem to be quite adequate. As an additional discovery, the stationkeeping thrust levels are greater than or on the same order as the GEO disturbance torques. This indicates that stationkeeping thrusts could be effectively combined with disturbance cancellation

5.0 APS/LSS INTERACTIONS

Interaction between auxiliary propulsion systems and large space systems were determined by constructing a matrix of the important APS characteristics against LSS characteristics. This matrix is shown in Figure 8. In order to establish the important APS characteristics, the requirements imposed by APS control functions were examined in turn. There are three basic control tasks: attitude control, shape control and stationkeeping.

	APS CHARACTERISTICS				
CONTROL FUNCTIONS AND LSS CHARACTERISTICS	THRUST LEVEL	MODULATION	RISE AND DELAY TRANSIENTS	NUMBER AND DISTRIBUTION OF THRUSTERS	SYSTEM MASS
DISTURBANCE CANCELLATION	X	X		X	X
POINTING	X	X	X		
MANEUVER	X	X			
SHAPE CONTROL	X	X	X	X	X
STATIONKEEPING	X	X			X
DESATURATION	X	X			X
LSS SIZE	X	X	X	X	X
LSS MASS	X	X			X
LSS LIFETIME	X	X			
LSS STIFFNESS	X	X		X	
LSS STRENGTH	X				
THERMAL EXPANSION					

FIGURE 8 APS/LSS INTERACTIONS MATRIX

Attitude control can be accomplished with APS directly or in conjunction with momentum exchange devices. Direct attitude control by APS requires, ideally, the delivery of precise torques to counter disturbances. The ideal can be closely approximated by delivering periodic torque impulse bits. It is clear that thrust level and modulation (amplitude in the continuous case and pulse width in the discrete) are important characteristics. Transient effects such as the rise and decay profiles are also significant particularly in limit cycle operation where they may impact accuracy and propellant consumption.

Shape control implies a distributed system in which APS units are spread over or through the vehicle structure. The number and distribution of thrusters is therefore a key characteristic. The control of shape requires the damping of structural modes and this means that timing becomes important. Continuous thrusts must be time varying or, when discrete pulses are used, these must be applied at precise times. Modulation and transient effects are thus significant.

Stationkeeping and desaturation are similar in that accumulated impulse is removed. In stationkeeping linear momentum that is unloaded while in desaturation it is angular momentum. Again the process can be either continuous or discrete and again the APS requirements are not demanding. The only important APS characteristic is the thrust level required to eliminate the accumulated impulse for a given thrusting time.

Consideration of the three basic control functions uncovered five important APS characteristics: (1) thrust level, (2) modulation, (3) rise and decay transients, (4) number and distribution of thrusters, (5) system mass. The first four characteristics are operating characteristics. From a system viewpoint, the total APS weight, while not directly affecting system operation, must also be considered. APS/LSS interactions were identified by looking at the five control functions (disturbance cancellation, pointing, maneuver, shape control and stationkeeping) in terms of the five auxiliary propulsion system characteristics (number and distribution of thrusters, thrust levels, rise and decay characteristics, modulation and allowable mass). In addition to control functions, system level characteristics also can interact with APS characteristics. System level items can include LSS size, lifetime, mass, stiffness, strength and thermal expansion. The matrix of Figure 8 was developed by considering each of the control and LSS characteristics against the five identified APS characteristics. Thermal effects were not found to have any general significant interactions with APS. Localized heating from APS units must, however, be considered in design.

Thrust level interacted with all LSS and control characteristics. With the exception of LSS strength, a sensitivity was also found between modulation and all LSS and control characteristics. Rise and decay transients affect

the precision control functions of attitude and shape control. They tend to become less important as size increases. An example of transient effects is shown in Figure 9 which shows the effect of a delay when damping oscillations of a plate structure. Typical frequencies are shown in Figure 10. While small delays are tolerable, it is seen that significant degradation occurs when the time constant becomes a large fraction of the oscillation period.

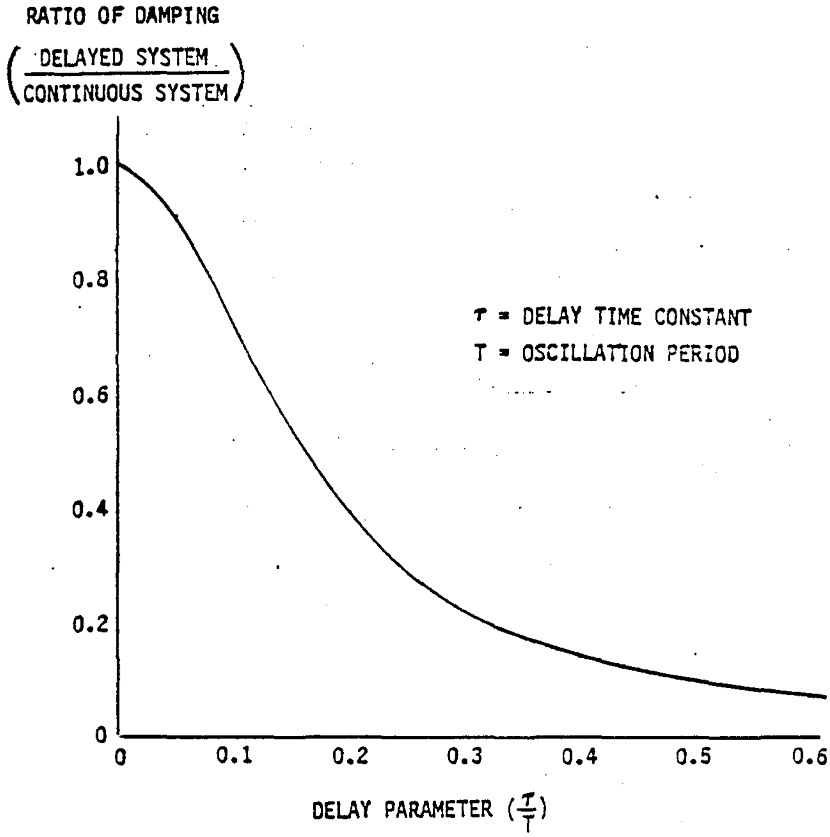

FIGURE 9 EFFECT OF TIME DELAY ON DAMPING

Number and distribution of thrusters interacts with shape control, LSS size and stiffness. Figure 11 shows the effect on deflection of distributing thrusters across a platelike structure. A considerable reduction in deflection is obtained with a modest increase in number of thrusters.

APS mass, as would be expected, interacts with a number of LSS and control characteristics. These include LSS size and mass and the control functions of disturbance cancellation, shape control, desaturation and stationkeeping.

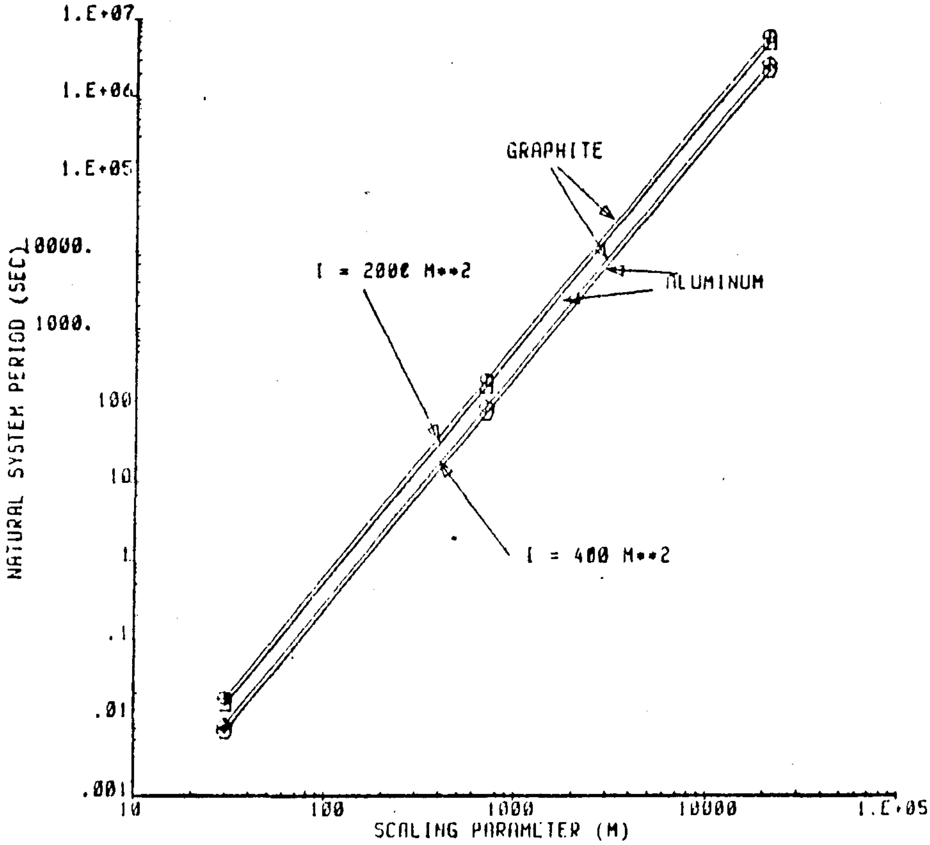

FIGURE 10 MULTIPLE SHUTTLE LAUNCHED PLATE STRUCTURE NATURAL PERIOD

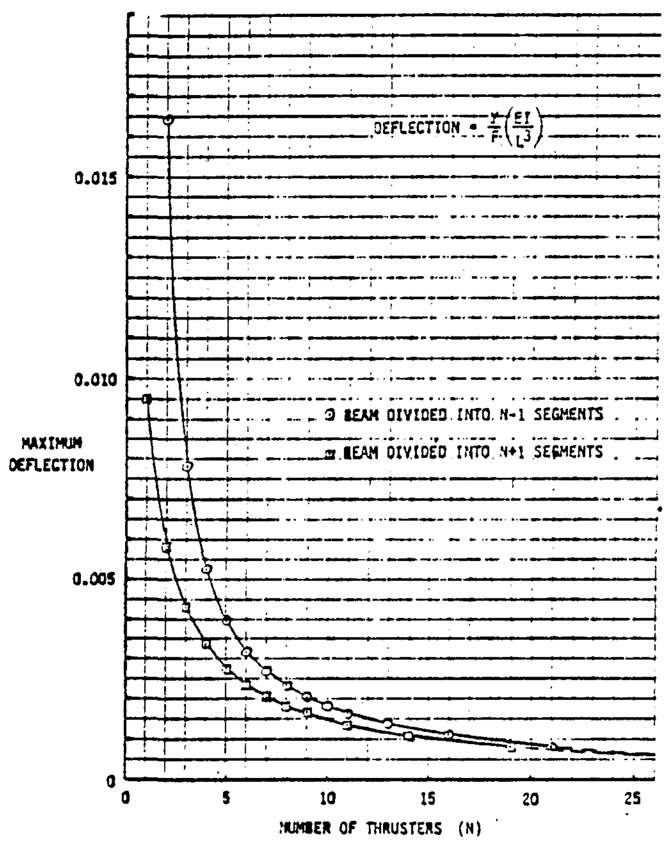

FIGURE 11 DEFLECTION DUE TO TRANSLATION

6.0 SYSTEM MASS DETERMINATION

In addition to defining the thrust level requirements and investigating the APS/LSS interactions, a study to determine the APS system mass characteristics for both electrical and chemical systems was undertaken. The primary independent variable used in this study was specific impulse. Other independent variables such as system efficiency, specific mass of power systems, and thruster mass scaling factors were briefly examined; however, the primary sensitivity study used specific impulse as the independent variable.

To determine system mass, a determination of the total impulse required for nominal stationkeeping for each structure assuming a ten year mission was made. A 10 percent conservatism was then added to this impulse number to account for uncertainties and recovery from off-nominal pointing angles. This determined the fuel mass and tankage mass requirement for a given specific impulse and fuel type. Thrust level requirements then sized the remaining APS hardware. The total APS mass and any additional area was then added to the structure and a new total impulse number for the total LSS was derived. This process was repeated in an iterative fashion until a total impulse number and an APS mass were defined. The system modelling equations used are shown in Table 6.

COMPONENT	UNITS	EQUATION
FUEL MASS	kg	M_p = TOTAL IMPULSE [1] / (I_{sp} x 9.81)
TANK MASS	kg	$T_v = M_p$ / SPECIFIC VOLUME OF PROPELLANT [2]
		$T_r = \sqrt[3]{\frac{3 T_v}{4 \pi}}$
		$T_a = 4 \pi T_r^2$
		$M_T = 5.62 \times T_a$
THRUSTER MASS	kg	$M_{Elec.\ eng.} = 12400.\ (T / I_{sp})^{.675}$
		$M_{Chem\ eng.} = .056\ (T) + .54$
POWER	w	$P = 9.307\ (T)\ (I_{sp}) / 2\ \eta_{sys}$
SOLAR ARRAY MASS	kg	$M_{S/A} = 13.5\ (P)$
SOLAR ARRAY AREA	m2	$A_{S/A} = 8.96\ (P)$
POWER PROCESSOR MASS	kg	$M_{PPU} = 2.1 \times 6.5\ (P)$

[1] Total Impulse = 110% Stationkeeping Impulse

[2] V_{SP} = 1 gm/cc CHEMICAL
V_{SP} = 13.5 gm/cc ELECTRICAL

TABLE 6 SYSTEM MODELING EQUATIONS

For the multiple shuttle launched LSS system, sizing was based on GEO worst case thrust requirements. Using this sizing assumption, electric systems always had lower mass than chemical systems. The specific impulse which minimizes the total APS mass (referred to here as the optimum specific impulse) for the electric systems is shown in Table 7 as a function of

total system efficiency. The specific impulse values increase with increasing system efficiency but in general decrease with increasing LSS size. For chemical systems, the optimum I_{sp} is simply as high as you can get it (maximum around 500 seconds) with regard to minimizing total APS mass.

The plate structure for multiple shuttle launched LSS was assumed to have power available for the electric systems because most of these missions were solar array power stations. This assumption was not used in the single shuttle launched LSS study which is presented below.

TABLE 7 OPTIMUM I_{sp} SENSITIVITY TO SYSTEM EFFICIENCY
MULTIPLE SHUTTLE LAUNCHED VEHICLES
GEOSYNCHRONOUS SIZING USED

STRUCTURE	SIZE	TOTAL SYSTEM EFFICIENCY			
		20%	60%	80%	100%
Plate	Small (30m)	5100 sec	9500 sec	9800 sec	10000 sec
	Medium (700m)	30000 "	50000 "	>50000 "	>50000 "
	Large (21000m)	>50000 "	>50000 "	>50000 "	>50000 "
Modular Antenna	Small (15m)	6000 sec	10500 sec	12000 sec	13000 sec
	Medium (60m)	5800 "	10000 "	10500 "	12500 "
	Large (200m)	1500 "	3200 "	3600 "	4000 "
Series of Antennas	Small (2)	7500 sec	11000 sec	15000 sec	15500 sec
	Medium (6)	5000 "	9000 "	10500 "	11500 "
	Large (10)	3600 "	7000 "	7500 "	9000 "

The stationkeeping delta-V requirements for the single shuttle launched LSS are shown in Table 8. A long duty cycle increases the total mission energy required because of cosine losses suffered by thrusting at non-optimal points in the trajectory. The plate w/blanket structure has the highest delta-V requirements due to the solar pressure contribution. Figure 12 shows the composite makeup of the stationkeeping delta-V for the medium sized (100 m) plate structure w/blanket. It can be seen from this figure that solar pressure can be a driver in determining LSS requirements at GEO.

For single shuttle launched LSS, the total LSS mass was calculated for four scaling assumptions. The system was sized for a 300 km - 10 degree LSS angle, a 500 km - 10 degree LSS angle, a 500 km - worst case LSS angle, and a maximum requirement at GEO. The LEO-GEO transfer scaling was not calculated because it is very similar to the 500 km worst case or 10 degree LSS angle (depending on class). This similarity is evidenced in Table 5. Two chemical I_{sp}'s and three electric I_{sp}'s were used. Figures 13 and 14 illustrate the results of this study for two LSS. Where it was not necessary to show all three electric I_{sp}'s to show a trend, the third was omitted.

The method used to calculate the total system mass for each scaling assumption is as follows. The thrust requirements for each sizing

TABLE 8
MISSION ENERGY REQUIRMENTS AT GEO
SINGLE SHUTTLE LAUNCHED DEPLOYABLE STRUCTURE
10 YEAR MISSION

CLASS	SIZE	STATIONKEEPING DELTA-V (M/S)		
		DUTY CYCLE		
		0.1	0.4	1.0
PLATE W/O BLANKET	30 M	539	576	835
	100 M	703	742	1078
	250 M	1062	1137	1672
PLATE W/BLANKET	30 M	953	1015	1480
	100 M	1093	1156	1701
	150 M	1123	1190	1742
MODULAR ANTENNA	15 M	578	617	904
	60 M	606	640	931
	200 M	734	781	1140
SERIES OF ANTENNAS	2	583	625	916
	3	583	625	916
	4	583	625	916

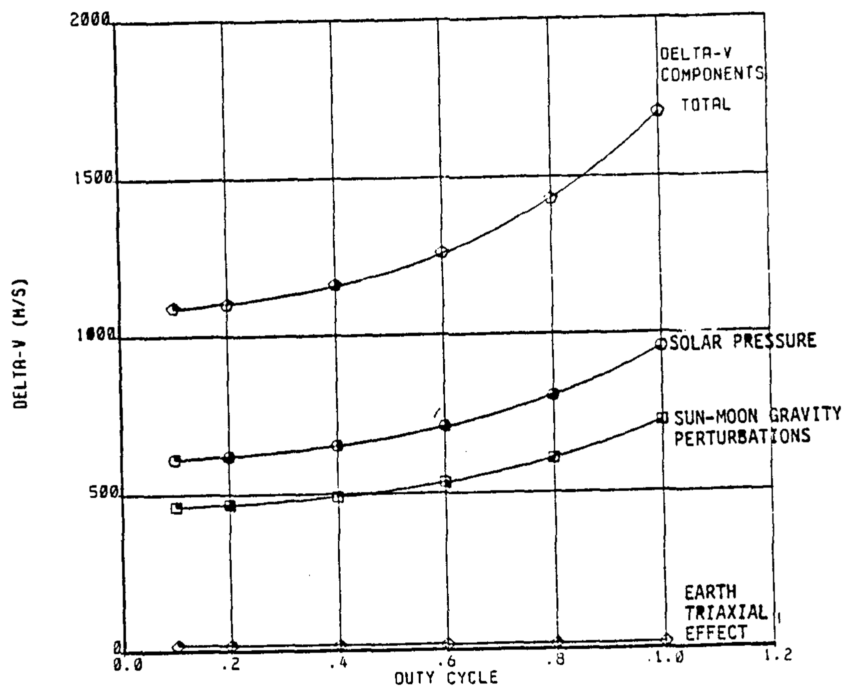

FIGURE 12
STATIONKEEPING DELTA-V COMPONENTS
SINGLE SHUTTLE LAUNCHED DEPLOYABLE STRUCTURE
PLATE STRUCTURE W/BLANKET MEDIUM (100 M)
10 YEAR MISSION

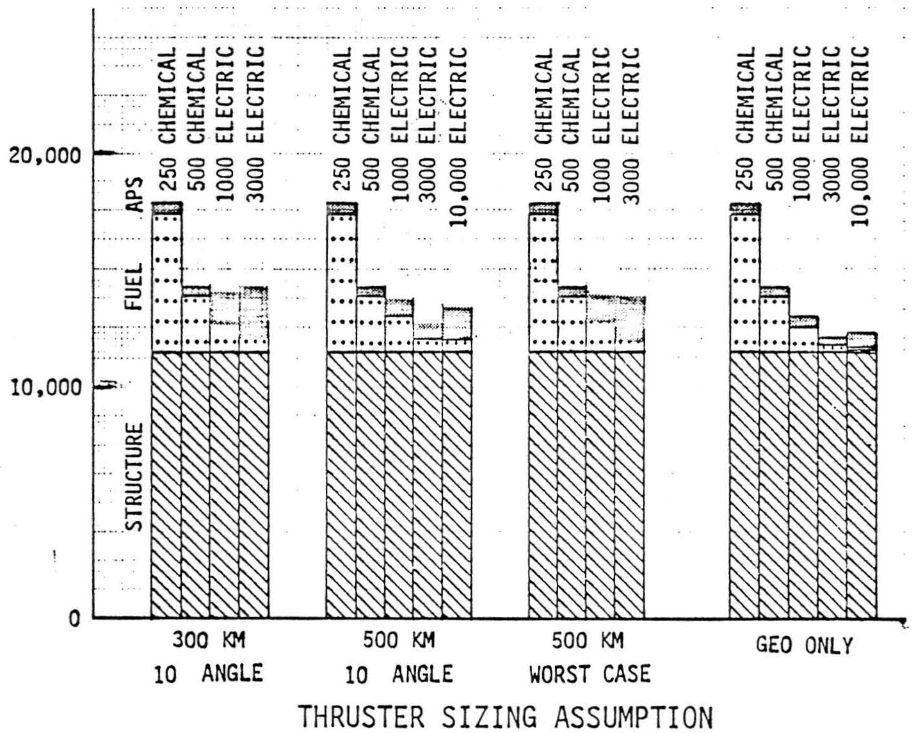

FIGURE 13 SYSTEM MASS COMPONENTS
SINGLE SHUTTLE LAUNCHED PLATE STRUCTURE W/BLANKET - MEDIUM (100 M)

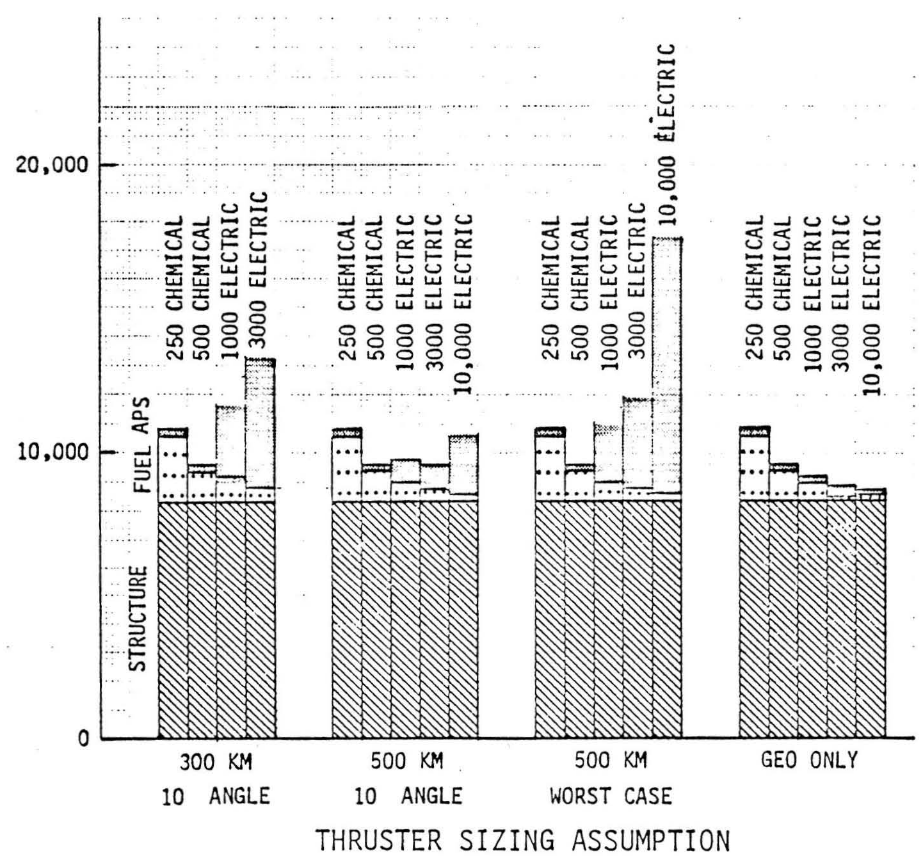

FIGURE 14 SYSTEM MASS COMPONENTS
MODULAR ANTENNA - MEDIUM (60 M)

assumption (300 km 10 degrees, 500 km worst case, etc.) would size the APS hardware. APS fuel mass, however, would be determined by calculation of GEO stationkeeping requirements with a 10 percent conservatism added. This method of scaling is consistent with the mission scenario assumed in this study - LEO deployment, LEO-GEO transfer and a 10 year GEO operation. Figures such as 13 and 14 were generated for each class and size of the single shuttle launchable deployable LSS. The results of this study showed that electric propulsion had a distinct mass advantage over any chemical system when the system was sized for GEO operation. For LEO thrust level scaling, the mass advantage depended on the chemical I_{sp} assumed. At 500 seconds I_{sp}, chemical systems showed a mass advantage for more than half of the categories examined. For a 250 second chemical I_{sp} assumption, only a few (6 out of 36) categories showed a chemical system advantage and this occurred primarily for the worst case LSS angle sizing. Where the mass advantage for electric systems in LEO existed, the size of the mass advantage was much less in LEO than for the same configuration in GEO.

As an additional output from the single shuttle launchable system mass study, optimum or minimum mass I_{sp} for the electric systems was determined. The results of this study are very dependent on the scaling assumption and on the size of LSS. Table 9 shows the optimum I_{sp} for each combination of class, size and scaling assumption. There are three trends evident in Table 9. The first is that as size increases, optimum I_{sp} decreases. This is true because the thrust levels required for the larger structures cause the power mass to dominate fuel mass at a lower I_{sp}. The second trend is that the optimum I_{sp} increases with increasing altitude. For most systems at 300 km, optimum I_{sp} is 2000 seconds or less whereas at GEO the optimum is around 6000 seconds or greater. Finally, the optimum I_{sp}'s at LEO are in most cases lower than SOA electric capability. This indicates that current ion systems may not be the most optimal electric system for LSS at LEO.

TABLE 9

OPTIMUM I_{SP} WITH RESPECT TO TOTAL APS MASS
FOR SINGLE SHUTTLE LAUNCHED LSS

SIZE LSS CLASS	SCALING ASSUMPTIONS			
	300 km 10^{o} ANGLE	500 km 10^{o} ANGLE	500 km W.C.	GEO ONLY
SMALL				
PLATE W/O BLANKET	2000	6750	6300	7400
PLATE W/ BLANKET	1800	6100	4400	6500
MODULAR ANTENNA	1600	6200	3400	>10000
SERIES OF ANTENNAS	4800	6200	3700	4800
MEDIUM				
PLATE W/O BLANKET	<1000	6200	4500	6800
PLATE W/ BLANKET	<1000	5800	3400	6300
MODULAR ANTENNA	<1000	2400	<1000	>10000
SERIES OF ANTENNAS	<1000	1000	<1000	5000
LARGE				
PLATE W/O BLANKET	<1000	5100	<1000	6200
PLATE W/ BLANKET	<1000	6100	<1000	6300
MODULAR ANTENNA	<1000	<1000	<1000	5800
SERIES OF ANTENNAS	<1000	<1000	<1000	5400

7.0 CONCLUSIONS AND RECOMMENDATIONS

The objective of this study was to characterize the APS requirements of LSS and, by comparing the required system to current SOA systems, to determine the direction auxiliary propulsion research and development should take to best meet upcoming needs. To define the areas of technology which need improvement to meet the requirements of LSS, five areas of APS characteristics have emerged as central issues in auxiliary propulsion of LSS. The six areas shown below form the outline of the study conclusions.

- o Thrust Level
- o Start-Up Characteristics
- o Number and Distrubution of Thrusters
- o System Mass
- o APS Lifetime
- o General Observations

7.1 Thrust Level

Thrust level requirements of both the large multi-shuttle lauched structures and the single shuttle launched deployable structures have been examined. The conclusions and recommended thrust levels are illustrated in Table 10.

TABLE 10 THRUST LEVEL CONCLUSIONS SUMMARY

	SINGLE SHUTTLE LAUNCHED DEPLOYABLE LSS	MULTIPLE SHUTTLE LAUNCHED LSS
LEO OPERATION		
300 km	Chemical required	Chemical required
500 km	10° LSS angle - SOA adequate Worst case angle - clustering required	
Recommended thrust/thruster (N)	1.5	5-60
GEO OPERATION	SOA adequate	Small LSS - SOA adequate Medium, large - clustering of up to 20 SOA elec. required
Recommended thrust/thruster (N)	<2	1.0

For the multiple shuttle launched structures, chemical systems have been found necessary to meet required thrust levels in LEO. LEO altitude for the multiple shuttle launched LSS was assumed to be 300 km. For GEO operations it was shown in Table 4 that some clustering would be required for electric thrusters to meet the requirements of medium and large erectable structures. Increased electric thrust levels to 1 Newton/thruster would capture the majority of GEO missions listed. Current thrust levels are adequate for the smaller structures listed in Table 4.

For the single shuttle launched LSS, current electric thrust levels are adequate with one exception for all GEO categories as shown in Table 5. In LEO, however, the difference between the 300 km altitude and the 500 km altitude requirements spell the difference between adequacy and inadequacy of current electric systems for some medium and large structures examined. The development of a thruster with thrust levels of 1.5 Newtons would capture the majority of the SOA uncapturable missions. Even moderate thrust increases such as 0.25 - 0.5 N above the currently available 0.13 N would be an enabling technology advance for many categories listed.

7.2 Startup Characteristics

Start-up delay was found to have significant impact in the areas of pointing accuracy and shape control. These results are summarized below:

- Pointing Accuracy
  - 30 minute start-up delay causes unacceptable accuracy loss (>1/2 degree) for structures 100 m or less in size.
  - 10 minute delay for small LSS (30 m) maximum allowable.
- Shape Control (when structural damping is required).
  - 30 minute start-up delay causes >60 percent reduction in structural damping for a 3000 m or less LSS size.

The APS/LSS interactions study showed that for medium and large multiple shuttle launched LSS, time delays of up to one hour did not significantly affect pointing accuracy. For structures of a few hundred meters or less, this effect is noticable. The minimum impulse bit of electric thrusters is somewhat ill-defined because even during startup periods a small amount of thrust is produced. Nominal electric thruster shutdowns are not "clean" but have a period of throttling down to the shut-off point. If one assumes a minimum impulse bit of 0.1 N-S, a 30 minute startup delay indicates a 0.45 degree accuracy loss for a 100 m structure which is unacceptable for some missions. Additional research to define the electric propulsion minimum impulse bit is needed before the full impact of startup delays can be evaluated.

7.3 Number and Distribution of Thrusters

A summary of the study findings regarding the need and implementation of distributed thrusters is presented and discussed below:

- o Distributed thrusters will be required for many medium and large (>60 m) LSS.
- o An optimum number of thrusters exists and is relatively small ($\sim$10) for any truss structure.
- o Electric thrusters can pose a much greater distribution problem than chemical thrusters due to thermal and power considerations.

After analysis of thrust level requirements had been performed, it became clear that for the medium and large size structures, the use of SOA electric propulsion units required large numbers of thrusters which for shape control reasons ideally should be equally distributed throughout the structure. Even with the larger thrust levels available with chemical thrusters, distribution of thrusters for classes IA (plate), IB (cross), IIA (box) is required for medium and large structures for shape control.

The number of thrust locations needed to minimize deflection reaches a point of diminishing returns. It was shown that after approximately 10 thrusters were distributed equally across a beam, the reduction in deflection by adding an additional thruster is minimal. Specific designs must be analyzed to study the interaction between beams on total surface deflections, however, this result may be applied generally in that there will always be a point of dimenishing returns for the distribution of thrusters.

Distributing thruster systems requires a distribution of system components over what may be very long distances. In the case of chemical systems, this poses no particular problem. For chemical systems, tanks, valves, and thrusters can easily be located as a unit with no interconnection between the units except for control electronics. Electric thrusters are a different matter. The high power required and inherently higher inert system mass for each APS unit dictates significantly greater system integration problems. Additional study to analyze these problems is indicated.

7.4 System Mass

The study conclusions in the area of system mass were very sensitive to the assumptions and LSS class examined. The conclusions are summarized and discussed below:

- o Multiple Shuttle Launched LSS
  - o Electric systems have the lowest total APS mass for most scaling assumptions.
  - o Optimum I_{sp} for electric systems assuming GEO scaling is 3600 to 15000 seconds.

- Single Shuttle Launched LSS
  - Chemical systems at 500 seconds I_{sp} have comparable total APS mass to electric systems when scaled for LEO thrust levels and GEO operation.
  - Electric systems have much lower mass than any chemical system when scaled for GEO thrust levels and GEO operation.
  - Optimum I_{sp} for electric systems varies widely according to scaling assumptions but an extended range of capability to <1000 seconds at LEO is indicated.

Throughout this study, specific impulse was treated as a variable for both chemical and electrical APS. We found that electric systems optimized over a wide range of specific impulse. Chemical systems have no power level dependence, hence always optimized at the highest achievable I_{sp}. In comparing the chemical and electric system mass for the large erectable structures using a geosynchronous requirement thruster sizing, it was found that in all cases electric systems had lower mass than chemical systems providing the optimum I_{sp} for the electric systems could be achieved.

Tables 7 and 9 presented the electric I_{sp} optimums under various assumptions. Under the assumptions used here, specific impulse range of current electric systems must be extended to much higher ranges than available. The plate structure needed higher than 50000 sec I_{sp} to optimize assuming the power source was not charged to the APS. If power mass was charged to the APS, a range of 3600 to 15000 sec I_{sp} is required to optimize system mass. The conclusions for geosynchronous orbit are the same for the deployable as well as the larger erectable structures. Electric systems have lower mass when sized for geosynchronous operation than do chemical systems.

LEO operation for deployable structures indicates that electric systems still have a mass advantage over chemical systems at an I_{sp} of 250 seconds. Chemical systems at 500 seconds, however, offset this advantage in many cases. LEO operation also requires lower specific impulse for electric systems. I_{sp}'s as low as 1000 seconds are indicated for LEO missions.

For both erectable and deployable structures, a general trend in specific impulse requirements was apparent. As the structure size increases, the optimum I_{sp} decreases. It is also true that as operational altitude decreases, optimum I_{sp} decreases. These facts are an indication that the thrust level demands at lower altitudes for larger LSS sizes cause the power level demands, hence, power system mass to be greater than fuel mass for electric systems. At geosynchronous altitude and for smaller structures at LEO, the power system mass required does not dominate the fuel mass required until very high specific impulses.

7.5 Lifetime

The lifetime and reliability demands on all systems comprising LSS are

drivers in LSS designs. System lifetimes of ten years or more with very high reliability (> 95 percent) will be required. These requirements indicate a need for redundancy management and operational schemes, both of which deserve future study. This study did not directly address these issues but a set of requirements for electric and chemical thrusters has been developed. These are summarized below:

- Electric Thrusters
    - For a 10 year mission with a 40 percent duty cycle (stationkeeping) a lifetime of 35000 hours is necessary (SOA $\sim$15000 hours).
- Chemical Thrusters
    - Up to 100000 valve cycles required for 10 year mission - (10^4 - 10^5 cycles yet to be demonstrated for 10N or greater thrust).
    - If hydrazine is used, catalyst bed life must be extended for 5 - 7 years up to 10 years.

For chemical systems, long term cryogenic propellant storage is a major issue. The specific impulse studies revealed that a chemical system of greater than 250 seconds I_{sp} is needed to compete with electric systems for single shuttle launched vehicles. This indicates a need for additional study to minimize the cost and system mass needed for 10 year or greater cryogenic storage. The second issue for chemical systems is hardware lifetime. Thruster value cycling and catalyst bed wear over the lifetime of the mision can be significant factors. Up to 100000 valve cycles will be needed for limit cycle operation over a 10 year mission. This does not appear to pose a problem for medium (1 - 10 N) thrusters; however, higher thrust cycling for 10^4 - 10^5 cycles has yet to be demonstrated. If hydrazine systems are used, catalyst bed life will have to be extended from 5 - 7 years up to 10 years.

Electric thruster lifetime and reliability are significant problems. For the 40 percent duty cycle proposed for geosynchronous orbit a thrust system lifetime of 35000 hours is indicated. Current systems have a lifetime of less than half this amount. Lifetime extension and verification testing as well as redundancy management analysis is indicated.

7.6 General Observations

Several general conclusions regarding LSS operations, control system component makeup, and APS operational philosophy emerged from the study. These conclusions are summarized and discussed below:

- Due to the relative equality of stationkeeping and disturbance torque thrust requirements at GEO, much attitude control effort can be obtained without cost by combining attitude control and stationkeeping. CMG's and inertia wheels may not be optimal controllers for many LSS.

- o Hybrid systems (chemical plus electrical) are indicated for systems which must perform at LEO and at GEO due to the large difference in thrust requirements.

- o Redundancy management and implementation techniques for distributed controls need development.

- o LSS operational philosophy (LEO vs. GEO deployment, LSS orientation, APS resupply) is a key driver to APS needs.

It had been assumed that many LSS would use momentum exchange devices such as inertia wheels and control moment gyros (CMG's) for attitude control. The trend towards this type of system seemed established in many of the preliminary design analyses conducted in recent years for vehicles which are large by present day standards. The LSS generic classes studied, however, showed that in most cases the stationkeeping requirements are equally as demanding as disturbances. Stationkeeping requires external forces which in GEO (and most LSS operational orbits were GEO) consist of both north-south and east-west components. Attitude control including disturbance cancellation, can be combined with stationkeeping (in two axes) and both functions can be performed simultaneously to a large extent, by careful system design. This means that little additional impulse is needed for attitude control if the stationkeeping requirements are satisfied. This being the case, momentum exchange devices lose their advantage and APS may be required to do the more demanding tasks of attitude control and in some instances shape control.

In examining thrust requirements, it became clear that the thrusts required varied by orders of magnitude with the higher values associated with LEO and LEO-GEO transfer. This being the case, the study groundrule, that thrust vector control (TVC) during transfer be supplied by APS, may, with benefit of hindsight, be unrealistic. It will probably be more cost effective to assume that TVC will be supplied by the prime propulsion system or that transfer will be achieved by a tug so that TVC on the LSS itself becomes unnecessary.

Another consideration is the big difference between nominal and maximum thrust requirements particularly in LEO. For example, many of the LSS considered had relatively small disturbance torques in their normal operating attitude but could experience very large torques in a worst case orientation. This problem is particularly severe with large structures since gravity gradient torques are functions of the inertias which go up with the square of linear size. In the past, the conventional wisdom held that APS would be sized to handle worst case situations. It may be time to abandon that guideline for large erectible LSS. If APS were sized to handle on-orbit nominal disturbances, plus some prudent reserve for contingencies, but not worst case conditions the APS requirements would be considerably eased. Worst case orientations could be treated as follows:

- o Design the system so that the probability of loss of control is sufficiently small that the danger of reaching a worst case condition is acceptable.

- o Carry a secondary APS for emergency use only. This could, for

example, be a high thrust chemical system. Presumably, emergencies would be infrequent so that the propellant needed, and thus the weight penalty, would be small.

- o Assume that a rescue vehicle would be available to effect emergency recoveries.

Any of these approaches would most likely be more cost effective than designing the APS to handle both the long term nominal torques and the short term emergency situations.

The study indicates that distributed thrusters and clusters of thrusters will be facts of life for LSS APS. This means that methods of controlling arrays of thrusters need to be developed. Questions of implementation, centralized vs. decentralized control, shared PPU's, location of tanks, redundancy management, etc., need to be addressed and solutions found.